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A state-of-the-art review and feasibility analysis of high altitude wind power in Northern Ireland

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ABSTRACT

In many countries wind energy has become an indispensable part of the electricity generation mix. The opportunity for ground based wind turbine systems are becoming more and more constrained due to limitations on turbine hub heights, blade lengths and location restrictions linked to environmental and permitting issues including special areas of conservation and social acceptance due to the visual and noise impacts. In the last decade there have been numerous proposals to harness high altitude winds, such as tethered kites, airfoils and dirigible based rotors. These technologies are designed to operate above the neutral atmospheric boundary layer of 1300 m, which are subject to more powerful and persistent winds thus generating much higher electricity capacities. This paper presents an in-depth review of the state-of-the-art of high altitude wind power, evaluates the technical and economic viability of deploying high altitude wind power as a resource in Northern Ireland and identifies the optimal locations through considering wind data and geographical constraints. The key findings show that the total viable area over Northern Ireland for high altitude wind harnessing devices is 5109.6 km^2, with an average wind power density of 1998 W/m^2 over a 20-year span, at a fixed altitude of 3000 m. An initial budget for a 2 MW pumping kite device indicated a total cost £1,751,402 thus proving to be economically viable with other conventional wind-harnessing devices.

Contents

Abbreviations: ABL, Atmospheric Boundary Layer; ABM, Airborne Module; AEP, Annual Energy Production; agl, above ground level; CAA, Civil Aviation Authority; CWT, Conventional Wind Turbine; CWT, Conventional Wind Turbine; DAFIF, Digital Aeronautical Flight Information Files; DBR, Dirigible Based Rotor; DBR, Dirigible Based Rotors; DOE, Department of Energy; EWEA, European Wind Energy Association; FCR, Fixed Charge Rate; GHG, Greenhouse Gases; GIS, Geographical Information System; HAWP, High Altitude Wind Power; ICAO, International Civil Aviation Organisation; LCOE, Levelized Cost of Energy; NCEP, National Centers for Environmental Prediction; NATS, National Air Traffic Services; PKG, Pumping Kite Generator; SUA, Special Use Airspace; TRL, Technology Readiness Level; UK, United Kingdom.

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1. Introduction

Over the past decade airborne module (ABM) generators have been conceptually developed to challenge both the technical and non-technical limitations of ground based wind power devices designed to operate in the atmospheric boundary layer (ABL), which is subject to intermittent winds both in magnitude and direction and heavily dependent on the surrounding interfaces. These conventional wind turbines (CWT) are constructed with heavy towers, foundations and blades that require huge investments and have associated problems of social and environmental acceptance due to obstructed views, noise pollution and threat to avian wildlife. The proposed ABM concepts have been developed to overcome these limitations around the key principle that wind speed increases with height [1]. Long-term field monitoring has been undertaken to study the ABL wind structure [2] and the neutral ABL has been approximated to a height of 1300 m [3]. At this height the ABM is exposed to higher velocity, steadier and more persistent winds, therefore resulting in a higher consistency of power generation [4]. The profile of wind power densities with respect to altitudes between 500 m and 12,000 m have been assessed globally [5]. The highest wind power densities were found at altitudes between 8000 and 10,000 m above ground level (agl), primarily due to the intercepting fast winds of both the polar jet and sub-tropical jet streams. These high power densities are important for wind energy development as wind power in the jet stream is roughly 100 times the power consumed on the planet by human activity [6]. High altitude wind power (HAWP) devices can conceptually surpass CWTs due to higher production capacity, more acceptable electricity cost, 90% less material consumption, higher societal and environmental acceptance because of lower visual and acoustic impacts and they operate well above the range of avian wildlife [7]. These devices can also be considered accessible in more locations because they have the potential to operate in land areas where CWTs would not be viable. This paper presents a techno-economic study of HAWP in Northern Ireland to examine the feasibility of this conceptual technology. This paper is divided into five main sections. Section 1 introduces. Section 2 presents a state-of-the-art review of HAWP. In Section 3 the techno-economic analysis of HAWP in Northern Ireland involving four steps is detailed. In step one, the potential of HAWP in Northern Ireland using online datasets (e.g. Earth System Research Laboratory) is estimated. In step two a map for easier visualisation of geographical limitations (e.g. airports, areas of scenic beauty, flight paths, military training areas, settlements etc.) that could impact on HAWP potential in the test system (i.e. Northern Ireland) is developed. In step three the actual feasible resource available is recalculated using the visualisation map to determine the 'optimal' HAWP locations in Northern Ireland. In the last step four the list of equipment, resources and budget needed to build a demonstrator is described in the form of a concise techno-economic appraisal using the findings of the previous three steps. Section 4 discusses the state-of-the-art review and the key findings of the study. Section 5 concludes and identifies the next steps for future research directions.

2. State of the art review

Several HAWP designs are currently being researched, but to date no fully operational proposals have emerged onto the market. These HAWP devices stem largely from the work carried out by Loyd [8] who proposed the concept of 'crosswind kite power' using tethered airplanes to harvest energy in the 1980s. Two main techniques were proposed to produce electricity from such a system. The first technique called the 'lift mode' uses kites to create tension within a tether to drive a ground-based generator to produce electricity. The second technique called the 'drag mode' employs a generator on-board the ABM driven by flying blades and transmits electricity to the ground via a tether [9]. Outlined below are some of the leading innovative HAWP solutions at varying stages of development.

2.1. Ground-based power generation

Ground-based power generation type HAWP devices exploit wind energy by means of kites. The operating principle of this device is to drive a ground-based generator using a tethered wing that flies in a lying-eight orbit taking advantage of high crosswind speeds [10]. At the ground station, the lower portion of the tether is wound around a drum that is connected to an electric generator. When the kite ascends into high altitudes, the high tension causes the tether to reel out, rotating the drum and consequently generating power. The tether is reeled back onto the drum using the generator as a motor in order to control the kite. The larger the tension difference during the reeling-in and -out phases of the tether, the greater the net power that can be generated [11]. This ground-based generation is also known as the 'pumping mode' or 'yo-yo' configuration due to the cyclic reel-in reel-out motion that generates alternating power. Principally, by either increasing or decreasing the angle of attack the tension in the tether can be manipulated by means of altering the lift force on the kite. Light flexible wings often designed by surf kite manufacturers are used for pumping kite generators (PKG), although there are marked differences in how the kite is steered and how many tether lines are used [12].

Opposed to flexible wings rigid wings can also avail of the pumping mode available to ground-based generation. These concepts comprise of autopilot-controlled glider planes that create tension on a tether by flying through high crosswind speeds [13]. The traction phase (reel-out) engages the tethered glider plane into an ascending mode thus performing figure eight fast loops until a maximum tether length is reached. The passive phase (reel-in) launches the glider into a vertical dive until a minimum tether length is achieved and the glider is positioned at the starting point to repeat the cycle. Although the alternating power generation produced by these devices has the potential to be problematic if connected directly to the grid. This can be overcome by connecting multiple devices working in tandem so that power generation is phased in frequency to produce a constant power output [14]. Significant losses in power generation would occur with these HAWP devices when carrying out maintenance procedures, such as wing or tether replacements or inspections..

An alternative ground-based concept is the carousel configuration developed for medium-to-large-scale HAWP generation. This HAWP proposal consists of several kites placed on the arms of a vertical-axis rotor positioned on vehicles moving along a circular rail path. A control system is designed to drive the flight of the kites so that the maximum torque can be exerted on each of the rotors to furthermore drive an electric generator. The torque opposed to the motion by the electric generator is controlled to have a constant rotation speed. The cycle is comprised of two phases, the traction phase and the drag phase. For a specified wind direction, each kite can generate electricity for 300° of the carousel rotation (traction phase) and only a small fraction of the generated electricity is consumed during the drag phase to pull the airfoil against the wind through the remaining 60° [29]. The major obstacle for this HAWP concept is the design of suitable robust kites and optimal flight control systems to obtain maximum generated power.

2.2. Multiple wing systems

Although optimal conditions for HAWP devices are located above and beyond the neutral ABL, these powerful, persistent winds create extra drag on the tether motion and limit the efficiency of the system. Concepts have been developed to address this issue by employing multiple kites on a shared y-shaped tether. The straight primary section enables the system to reach high altitudes with little swaying movement thus allowing each of the airfoils to operate on either end of the shorter secondary tethers (ν-section). This configuration was compared to a single tethered airfoil and was found to extract more power due to reduced tether drag losses [15].

Another method in which power can be generated via the pumping mode is the laddermill concept. This is a 1 km high self-supporting looped tether with a series of high-lifting wings that move up in a linear fashion combined with a series of low lifting wings that go down, known as the translator [16]. On the ascending end, the wings can be adjusted to deliver maximum lift, while on the descending end; the low-lifting wings provide just enough lift for the system to stay aloft. This HAWP device passes through the ground station with every full rotation allowing for frequent inspections thus minimising downtime. This HAWP device can also be easily adapted to changing wind speeds by varying the number of wings attached or altering the tether length. However, the inefficient use of material by this HAWP device is an issue because half of the loop that is descending makes no contribution to electricity production [14]. Furthermore, the excessive weight of the system reduces both the tension produced by the up-lifting wings and the tether speed thus lowering power generation overall. The PKG is a more lightweight simplistic option because it only requires half of the required material.

2.3. On-board power generation

This type of HAWP device is associated with Loyd's 'drag mode' technique as it requires the ABM to carry a turbine on-board. These HAWP devices generate crosswind power through exposure to high relative airspeeds forcing the rotors to rotate and consequently produce electricity. This electricity is then transmitted to the ground by the means of a flexible tether. This idea of using 'propellers on-board a self-erecting structure' was first introduced by [17]. A 'variant of a gyroplane' with quadruple rotor arrangements mounted on an airframe to simultaneously generate lift and electricity was developed by Roberts et al. [18]. This concept is that this HAWP device would be located in the upper atmosphere, 4.6 km and above, harnessing wind energy from the vigorous jet streams. The rotors are controlled and optimally adjusted into the oncoming wind. This ABM can launch and land similar to a helicopter by supplying a small proportion of power from the ground with the generators operating as motors.

2.4. Dirigible based rotors (DBR)

This on-board generated power approach is based on aerostat technology, which relies on a lighter-than-air gas filled balloon to keep the heavy payloads aloft rather than relying on lift generated via rotors [11]. These HAWP devices are advantageous in low intermittent winds, as the aerostat can remain airborne without consuming power. Researchers at Massachusetts Institute of Technology have developed a functional prototype that is comparable to an observation aircraft concept developed by NASA, which is powered by a traditional horizontal axis turbine [19]. This device is designed for 'fast, passive alignment into the wind' that operates at high attitudes of 600 m. This device does not avail of crosswind power but functions by the means of a stationary aerostat [20]. This HAWP device has been designed to be fully autonomous, from take-off, through operation, to landing onto the transportable ground station, thus making this device an ideal application for emergency power relief in disaster stricken areas [21]. Other approaches have combined the 'pumping mode' with the aerodynamic phenomenon known as the Magnus effect. This occurs when a DBR device is rotated while ascending to higher altitudes, which in turn lowers the drag effect of the wind, thus reverting it to lift mode [22].

2.5. Markets, materials and components

Numerous innovative approaches have emerged to harvest high altitude winds for power production and some are shown in Table 1. Although, none of these HAWP devices have as yet has been launched commercially they have been progressing through various research and development phases. The technology readiness level (TRL) has been included in Table 1 to 'assess the maturity of evolving technology' and it consists of nine levels, beginning with a concept (level 1) to full deployment of the product in the marketplace (level 9) [57]. Some have advanced to the prototyping stage as patented technology.

2.6. Airborne module (ABM)

The three most prominent approaches to harness high altitude winds using an ABM are tethered kites, rotorcraft and balloons. Kites have generated a growing interest as a result of the need to generate renewable energy. There are different types of commercially available kites that can be employed, such as ram air kites, with air inlets at the leading edge and leading edge inflatable kites. Delft University of Technology has developed a kite concept for high altitude winds called the 'kite plane', the design is primarily

Table 1
High altitude wind power concepts.

Figure	Name	Location	Technology	TRL	Patent no.
 **KiteGen STEM**	KiteGen [58]	Italy, EU	This device employs the 'pumping mode' using a dual tether power kite, elevated at 1000 m. The control system automatically pilots the kite to generate maximum power.	6	EP 2,010,783 A1 [61]
 **Makani 20 kW Prototype**	Makani [39]	California, USA	This concept is a tethered airfoil with on-board power generation, creating lift and power. They have developed a 600 kW prototype, operating at an altitude of 140–310 m.	6	US 20,130,221,679 A1 [62]
 **Buoyant Airborne Turbine (BAT)**	Altaeros energies [59]	MIT, USA	This DBR ascends to altitudes of 600 m due to the helium filled shroud, and is powered by a horizontal axis wind turbine, generating 2–3 times the amount of power from a CWT.	7	US 20,120,319,407 A1 [63]
 **Magenn Air Rotor System (MARS)**	Magenn Power [60]	Canada, CA	This helium filled DBR is tethered at each end with rotating generators. Its body has fans attached to catch the wind, rotating the device, creating the Magnus' effect. It is situated 600 m above ground level, with an efficiency of 40–50%.	7	CA 2,607,103 A1 [64]

based on 'tube kites' used for surfing [23]. The structure of the kite plane consists of 'inflatable beams and canopy panels.' The inflatable beams provide structural rigidity and can be sealed air tight to contain a gas. Woven fibres are commonly used for kite applications, such as 'rip-stop nylon' for parafoil type kites and 'rip-stop polyester' as the canopy material for tube kites. Dacron is a heavier polyester cloth used to reinforce the tubular frame of tube-kites containing Kevlar [24]. Kites are considered a favourable concept as it is believed that they would survive crashes better. Kites can be designed to be extremely lightweight for a given surface area but rely on the aerodynamic load distributed airflow to maintain their shape [12]. In terms of tethered rotor craft, Makani Power have utilised carbon fibre for their rigid wing spar due its high tensile strength-to-weight ratio and for the wing skin, e-glass is proposed as it restricts the amount of ultraviolet and infrared light that can pass through thus reflecting heat [25]. The benefits of a rigid wing ABM is that shape is maintained independent of the ambient wind conditions and due to its higher lift to drag ratio it can reach high velocities resulting in a significantly higher power output per wing area. However, a rigid wing structure has the potential to have major consequences in the event of a crash, thus causing considerable damage. Laminates can be tailored by layering materials with varying properties into a material with particular properties. Laminates are commonly used in lighter-than-air applications, for example in DBR devices that combine high modulus fibres such as Vectran or Kevlar to carry load [23].

2.7. Tether

The two main functions of the tether are to control and position the ABM at high altitudes and to transmit electrical power for on-board power generation systems and DBR devices. The material properties of the tether are important as a tether needs to withstand strong tensions due to the powerful, high velocity winds. Furthermore a tether is subject to strain due to ascending and descending the ABM load, elongating the tether [14]. A high voltage tether is required to transmit the electricity to ground level, although the weight of the tether is an important constraint due to the effects of tether drag. For their current prototype, Makani Power have chosen a copper conductor within a dyneema fibre [26] structure owing to its tensile strength of 11,000 MPa, which is'15 times stronger than steel' and its load distribution properties. The Sky WindPower team have instead utilised a 10 mm tether with lightweight aluminium conductors in a Vectran fibre composite. Vectran is a multifilament yarn spun from liquid crystal polymer similar to that of Kevlar with 'exceptional strength, rigidity and modulus' [27]. Both of these concepts are still at the prototyping stage and it is not known how resilient these materials will be in the demanding and harsh jet-stream conditions. A potential developing solution is carbon nanotube technology [28]. This extremely strong (up to 60 GPa) lightweight high conductive tube-shaped material would allow HAWP technologies to operate at greater altitudes with lower drag and transmission losses.

2.8. The ground station

Altaeros energies utilise a portable ground station built onto a trailer platform so that it can be deployed in any location [59]. The system is fully autonomous, does not require large grounding crews. and mounts safely on landing rails to secure it when docked. Winches on the ground station control both tether length and speed and correct alignment to prevent the tethers from tangling. The ground station also conditions the electricity produced before connecting to the grid. Makani power docks the tethered rotorcraft at its ground station when not in use or in critical weather conditions.

2.9. The system control unit

The System Control Unit is designed to monitor the overall performance of the HAWP device through data transmission from on-board sensors. The main objectives of the System Control Unit is to maximise electricity generation and to ensure that all components are in good working condition and not exposed to excessive workloads or damaged by the high altitude conditions. The core of the KiteGen STEM System Control Unit is the kite steering unit, which consists of the electric drives, drums, winches and all on-board hardware [29]. The Delft University of Technology HAWP device uses a single tether line for their pumping mill concept, as well as an electronic kite control mechanism, which allows the kite to be steered from the ground by changing the attachment point position on the sides of the kite [30].

2.10. Viability

Although there are countless advantages to employing HAWP technology there are many technical challenges that must be addressed if this technology is to become feasible. Safety limitations are a major concern, for example, some HAWP technologies operate in the same airspace as cruising altitude airplanes, the proximity of populated settlements, or motorways or power lines in the scenario of the ABM crashing down. To address these safety limitations, restricted airspace zones could be allocated for HAWP devices, with lights and markers to improve visibility of the device, or an on-board transponder that signals to other airborne radars to restrict proximity. There is also an intermittency issue with HAWP systems. Although at higher altitudes winds are much stronger and steadier they are still variable meaning that energy storage systems are required to provide a steady smooth electricity supply to the grid [31]. Numerous storage systems exist, such as compressed air, battery arrays, flywheels or ultra-capacitors, which are selected dependent on the power output and operating altitude of the application. The purpose of these systems is to store energy when production exceeds demand and then reversely discharging this energy when demand exceeds production [5]. Seasonal changes can also shift the jet stream location causing changes in wind intermittency. Ground-based stations situated along the seasonal route of the jet stream have been suggested to relocate the HAWP devices in order to avail of a higher generating capacity [32].

Due to these systems operating in the harsh conditions of the jet stream, frequent maintenance will need to be undertaken, particularly for on-board electricity generation systems where there are numerous moving parts. This maintenance will incur significant downtime and costs due to specialised parts and labour. The scalability of HAWP devices also poses challenges due to the airborne size and weight constraint. Although Sky WindPower claims that their HAWP devices efficiency will improve with scale as the ‘tether strength-to-weight ratios and guidance control weight improve as sizes scale up’ [33]. This claim has not been demonstrated in reality. Exposed to the atmospheric environment, the occurrence of lightning strikes presents a further threat to HAWP systems. If a lightning strike occurs, there is a risk that the ‘tether will attract the lightening leader and develop via it or be subject to a surface flashover’ [34]. This could lead to a breakdown of the tether due to the strong static electric field generated by a charged thundercloud, or worse, if the current is transmitted downward, it could severely damage the ground-based generator. A measure that could be undertaken to protect the ground-based generator would be to bypass the conducted lightening to ground using an earthing system.

2.11. Other applications

An alternative use for HAWP devices is as a propulsion system for ships. The German company, Sky Sails Power [35] are the leader in this domain with a patented ‘towing kite propulsion system’ for cargo ships. A fixed length tether line connects a parafoil to a ship that has no relative translational motion other than to pull the ship. In good wind conditions Sky Sails Power claim that this technology can replace 2 MW of power from the engine daily saving ’10 t of oil’. Sky Sails Power has also developed an offshore power system operating at altitudes up to 800 m. It can be installed on both CWT offshore platforms or floating platforms anchored to the seabed. This technology uses the pumping mode as a means of electricity generation. Another proposed use for the electrical power produced from HAWP devices is in naval propulsion systems applications to electrolyse seawater on-board to produce hydrogen or methanol or ‘convert carbon dioxide into storable forms of liquid’ [36]. These by-products could be stored within tanks on board a ship and be unloaded to either a courier tanker or at port. These innovative novel technology proposals are a prime example of clean renewable energy obtained from the wind without releasing greenhouse gases (GHG) into the atmosphere. However, many challenges must be overcome in order for this technology to become feasible, relying primarily on advancements in science and technology and precautionary policy measures to protect civilisation. Hence the promise of inexpensive zero-carbon and abundant wind energy will continue to drive the development of HAWP devices.

3. Techno-economic model and mapping

3.1. Wind data acquisition

The high altitude wind data used in this analysis was obtained from the National Centers for Environmental Prediction (NCEP) and the Department of Energy (DOE) AMIP-II Reanalysis (Reanalysis-2) [37]. The NCEP/DOE AMIP-II Reanalysis (R-2) provides an updated 6-hourly global analysis of atmospheric variables such as wind and temperature with 143×73 grid points in the horizontal with spacing of 2.5° ranging from the year 1979 to the present [38]. NCEP/DOE Reanalysis (R-2) datasets are a reliable source to resolve upper level winds to carry out the first global assessment of HAWP. These datasets were first in 2009 to examine HAWP at between 500 and 12,000 m agl [5]. The daily averaged wind data for Northern Ireland was extracted over a 20-year span, from 1993 to 2013, setting the area boundaries within latitude of 52° to 56°N and a longitude of 5° to 9°W, over pressure levels ranging from 10 mb to 1000 mb. The wind data was collected on a yearly basis in the form of u-wind and v-wind vector datasets, within a Unidata's Network Common Data Form (NetCDF) file format.

3.2. Wind power density

As one of the main objectives of this work was to assess the potential of HAWP in Northern Ireland code was developed in MATLAB to manage, filter and pre-process the wind data from the NetCDF file format and then to undertake the subsequent data analysis and visualisation of high altitude wind speeds and power for the study area. Once the wind power density across Northern Ireland was determined the data was averaged over height, available area and for a time span of 20 years., Furthermore the results were plotted on a coloured contour spatial chart using the Mapping Toolbox within MATLAB. The maximum height for averaging was set to 3000 m as this covers the majority of proposed operating altitudes by established HAWP companies in the market presently.

3.3. Geographic information system (GIS)

In order to determine the possible locations for siting a high altitude wind-harnessing device, the actual conception of such a system must be considered. All HAWP systems have an ABM, such as kites, rotorcraft and balloons, which are tethered to a ground station. Presently it is unknown as to what will be the commercial available size of these HAWP devices, although Makani Wind power have proposed a 65 m wingspan device for offshore wind [39], while Sky Wind Power intend to deploy a four-rotor 3.4 MW configuration with an estimated weight of 9500 kg [6]. Therefore it is apparent that safety ultimately is the primary concern when locating sites for these devices and eliminating any areas that may impose possible danger to civilisation in the event of an ABM crashing down. This concept of safety is illustrated in Fig. 1.

3.4. Safety on the ground

The potential failure of either the ABM or the tether must be considered with regard to ground safety. In the event of an ABM failure, such as rotor failure due to mechanical malfunctions, the worst-case scenario is that the radius of influence will be the tether length, as the ABM will be still fixed to the tether. A fatal tether failure for a Makani or Sky Wind Powers HAWP the onboard generating systems could land safely with the use of their rotors controlled by a ground based pilot given that there is storage energy available otherwise the device could float away. Makani has implemented a supervisory control and data acquisition system that will control and monitor the health of the device including sensors to detect impendence in individual sections of the tether [65]. Regardless, an electrified tether could possibly fracture and descend to the ground for any of the HAWP concepts. This could be detrimental to surrounding infrastructure as a carbon fibre/aluminium tether could weigh up to 3660 kg for a 5 MW Makani HAWP device [33]. Therefore in the event of tether failure the minimum radius of influence again will be the tether length to alleviate the risk to civilisation until operating experience assures the operation of HAWP devices. In reality these devices will be concentrated within a HAWP farm to prevent the possibility of one ABM colliding with another and so an adequate spacing distance must be ensured between each ABM. The minimum spacing distance considered is again the maximum tether length.

3.5. Airspace safety

A range of tether lengths have been proposed by HAWP developers dependent on an optimal operational altitude, amongst the proposed tether lengths are some as great as 4.6 km [40]. This would imply that these HAWP devices would need to be situated within a dedicated restricted airspace from other commercial and private aircraft to prevent the disastrous consequence of a mid-air collision. In the United Kingdom (UK), the Civil Aviation Authority (CAA) governs the operations of tethered balloons and kites, subjecting them to the provisions and requirements set out in Articles 163 and 164 of the UK Air Navigation Order, (CAP 393) [41]. The UK Air Navigation Order raises a concern with “visual acquisition of cables” presenting a significant safety hazard to other airspace users and that long-term or overnight operation above 150 m must take place within segregated airspace. Any such tethered device would also have to adhere to Rules 52 and 53 of the Air Regulations [42] which specifies that a tethering cable exceeding 60 m needs to be fitted with specific high intensity lighting and markers to ensure detection in all directions. In addition, operating a balloon above 300 ft would need to be notified to the wider aviation community through the use of a transponder. In the context of airports, the International Civil Aviation Organisation (ICAO) has outlined an aerodrome standard, stating that “high-intensity obstacle lights at night may dazzle the pilots in the vicinity of the aerodrome” [43]. As a consequence, a 10 km-restricted radius is imposed between the approach to a runway and high obstacles.

3.6. Geographical limitations

Several ‘geographical limitations’ have been identified as layers within the test system analysis to ensure the safety of society and infrastructure surrounding a potential HAWP farm. These geographical limitations are:

- Motorways – These high-speed lanes have been selected in precedence to regional roads, as the traffic is more concentrated and has a shorter time to react if a HAWP device was to undergo system failure and crash. This data was sourced from a 1:50,000 full vector dataset of Northern Ireland provided by Ordnance Survey of Northern Ireland (OSNI) [44].
- Railways – This data was sourced from 1:50,000 full vector

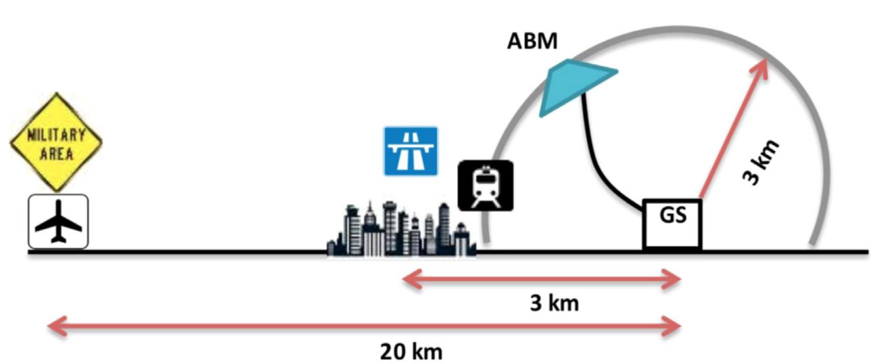

Fig. 1. Schematic view of safety concept when HAWP devices in operation.

dataset of Northern Ireland provided by OSNI.

- Settlements – 'Large towns' and 'towns' were filtered from the settlement data contained within the OSNI 1:50,000 full vector dataset of Northern Ireland. These areas take precedence over 'villages' and 'small villages', not only due to greater population concentrations but also due to their transport infrastructure.
- Airports and Military Training Areas – The data for civil aerodrome locations was sourced through the Google Earth application and plotted onto an OSNI outline map. Military training areas were sourced from a chart published by the National Air Traffic Services (NATS) that displays Airspace Restrictions and Hazardous Areas in the UK [45].
- Controlled Airspace – Special Use Airspace (SUA) and Digital Aeronautical Flight Information Files (DAFIF) data was sourced for the Northern Ireland region identifying restricted air corridors in the vicinity of airports but also segregated areas restricted for alternative aviation activities such as hand gliding, paragliding, and sky diving [46].
- Protected Areas – To ensure both wildlife and natural landscapes are preserved, special areas are designated for protection, including Areas of Outstanding Beauty, World Heritage Sites, Areas of Special Scientific Interest and Special Areas of Conservation. These areas have been included as limiting layers due to the stringent planning permission restrictions to any major developments. This digital data was sourced from the Department of the Environment (DOE) [47].

3.7. Over laying using ArcGIS

A key objective of this work was to identify and display the geographical limitations that could impact on high altitude wind power potential sites, and furthermore based on the limitations, identify the optimal high altitude wind power locations in Northern Ireland. Through researching various geospatial-processing programs, ArcGIS was deemed the most suitable to realise this objective [48]. ArcMap allows for data exploration from various data formats and in addition can create layers used to display a specific GIS dataset, symbolising features accordingly. The geographical limitations data outlined above in Section 3.6 were transformed into individual layers within ArcMap using the Irish grid coordinate system. A radius of influence, using the buffer tool was applied to layers that were subjected to the safety concept outlined in Fig. 1.

For motorways, railways and settlements a 3 km radius was used, while for airports and military training areas, a general 20 km radius was applied, given that the chosen operating altitude is 3000 m. A final visualisation map is obtained by over layering all the mentioned geographical limitations and geo-referencing this result onto the preliminary high altitude wind power map, revealing the optimal locations for high altitude wind harnessing devices.

3.8. Project demonstrator cost model

As HAWP technology is still premature and presently not commercially available on the market, it is difficult to calculate the economic parameters of such a device. In order to prepare an initial budget for the project demonstrator for the test system, a cost model for Year 1 was created based on the KiteGen STEM 2 MW PKG [49], primarily as this is the only HAWP device developer that has published sufficient design parameters to carry out a preliminary cost analysis. These design parameters are shown in Table 2. As certain aspects of a PKG are similar to those of a CWT and others are dissimilar, a mixture between both technologies is used for this cost analysis.

Due to the unique design of a PKG the cost estimations of some components can be difficult to estimate as they are not commercially available or there are no comparable products. To address this uncertainty, two cost boundaries are established, a lower boundary based on pessimistic assumptions and an upper boundary based on more optimistic assumptions for the kite, control system, tether and mechanical system components. A life span of 1000 h was assumed for the control system. A cost of £5.00 per m^2 was assumed for Nylon Polyamide/Nylon sourced from Alibaba for an area up to 30 m^2 and it was assumed that four material layers were used. A factor of 4 is applied to compensate for the increase in price for a HAWP with a lifespan of 1000 h, as it is most commonly 100 h for kite surfing applications.

Table 2
Model parameters.

Kite mass, kg	300
Characteristic area, m^2	500
Lift coefficient	1.2
Kite aerodynamic efficiency	13
Diameter of a single line, m	0.03
Line density, kg/m^3	970
Line drag coefficient	1.2
Minimum cable length	850
Air density, kg/m^3	1.2

The cost model for the electrical systems of a PKG was determined using cost factors established from an economic study of airborne wind energy [50], which was based on the assumption that the "drivetrain of a PKG can be built similar to the drivetrain for a CWT." The cost functions for the electrical systems are derived from CWT data [51,52] and manipulated for a PKG to include a generator, power electronics, yaw drive and bearings, a ground station and a hydraulic and cooling system. The balance of station costs account for the resources that are needed on-site for a project demonstrator to include a foundation, road construction, an electrical installation and a grid connection. These estimations were taken from a report from the European Wind Energy Association (EWEA), which details the cost structure for a typical 2 MW wind turbine installed in Europe [53], allowing for adjustment based on assumptions made for a PKG. These assumptions included taking 10% of a CWT foundation cost as there is no tower structure, taking 30% of the CWT road construction costs as crane pads are not necessary only gravel roads and taking 50% of CWT electrical installation costs as there is no tower, therefore wiring can be limited to a minimum. Annual operating expenses account for the annual cost of owning and operating an asset over its entire lifespan. Replacement costs for the PKG are considered based on associated lifespan for the kite (1000 h), tether (10,000 h) and kite control unit (5 years), as well as operations and maintenance, which was estimated at a cost of £10,000 per year and taking a land lease of 30% of a CWT [54].

3.9. Results and analysis

Fig. 2 displays the preliminary spatial distribution of wind power density for Northern Ireland without any limitations, averaged over a 20-year time span from 1993 to 2013, at a fixed pressure level of 700 mb equivalent to a height of 3000 m. The average wind power density over all pressure levels from 10 mb to 100 mb is displayed in Fig. 3 with corresponding pressure heights ranging from 111 m to 25,919 m over a 20-year time span across Northern Ireland. Fig. 4 represents the absolute wind velocity and equivalent pressure level height averaged over a 20-year period across Northern Ireland. Fig. 4 represents the absolute wind velocity and equivalent pressure level height averaged over a 20-year period across Northern Ireland.

Fig. 5 displays the geographical limitations identified in Section

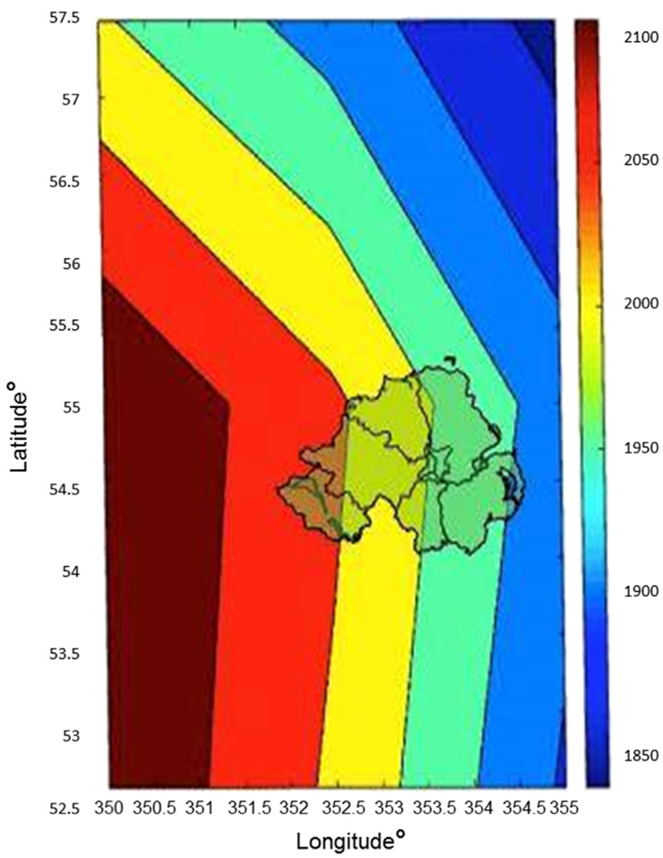

Fig. 2. Preliminary wind power density (W/m^2) for Northern Ireland without limitations.

3.6 and include a radius of influence in adherence to the safety concept illustrated in Fig. 1. These areas are deemed to be unsuitable locations for HAWP devices. In Fig. 6, all identified limitations (i.e. i–viii) are overlaid and placed upon the preliminary high altitude wind density map, shown in Fig. 2, leaving discernible the optimal sites for HAWP devices in Northern Ireland with the associated wind power resource available. All images marked with ‘a’ in Figs. 5 and 6 are based on Land and Property Services datasets reproduced with the permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright and database rights MOU203. All images marked with ‘b’ in Figs. 5 and 6 is based on © Crown Copyright and is reproduced with the permission of Land & Property Services under delegated authority from the Controller of Her Majesty's Stationery Office, © Crown Copyright and database rights, EMOU206.2 Northern Ireland Environment Agency Copyright 2014.

The final visualisation map in Fig. 6 presents the available areas for siting a HAWP device with an associated average wind power density at 3000 m agl. The total viable area across Northern Ireland for siting HAWP devices was determined to be 5109.6 km^2 using the ‘Data Overlay’ feature on ArcGIS. It is evident the most abundant high wind power densities occurs off the west coast of Northern Ireland, attaining wind power densities in excess of 2050 W/m^2. Through over layering the geographical limitations presented in Fig. 5, it is apparent the most limiting layers, in terms of available area, are controlled airspace and areas of outstanding natural beauty. Potential onshore HAWP locations are dispersed with the greatest area coverage situated in the southern part of County Tyrone in the west of Northern Ireland, although yielding a lower wind power density, in the range of 1950 W/m^2 to 2000 W/m^2, to that of the optimal sites but with limited area coverage in County Fermanagh in the west of Northern Ireland and western County Tyrone with a power potential of 2050 W/m^2 or above. The eastern areas in Northern Ireland are heavily restricted, primarily due to the capital city of Northern Ireland (i.e. Belfast) being located within this area, with greater populations and therefore higher settlement concentrations, major roads and railway intersections and two adjacent airports. The northern areas yield two sizeable, potential locations, including a wedge shaped area situated on the north coast of County Antrim in the east of Northern Ireland, with a reasonable potential of 1925 W/m^2 to 1950 W/m^2, although a more feasible area borders the counties of Antrim and Derry/Londonderry, harvesting a higher wind power density for power production in the range of 1975 W/m^2 to 2000 W/m^2. The most suitable site for a demonstrator HAWP farm is in the western area of County Tyrone, due to the greater available area free from limitation, allowing for possible expansion for siting a farm of HAWP devices. However, these findings lead to the suggestion of a follow-up feasibility study for the Republic of Ireland, in particular County Donegal, situated to the west of Northern Ireland, as it borders the optimal site for HAWP in Northern Ireland.

To determine the variation in HAWP density over the course of a year at the selected height of 3000 m, an analysis was carried out on a per-month basis, averaging over a 3-year time span from 2010 to 2013, shown in Fig. 7. Variations were found to be 80%, based on minimal and maximal values of 3792 W/m^2 and 763 W/m^2, illustrating HAWP is susceptible to seasonal changes, putting forward the proposal of introducing ground based stations along a ‘seasonal route’. However, this variation would be expected to decline if the analysis was carried out over a larger time span.

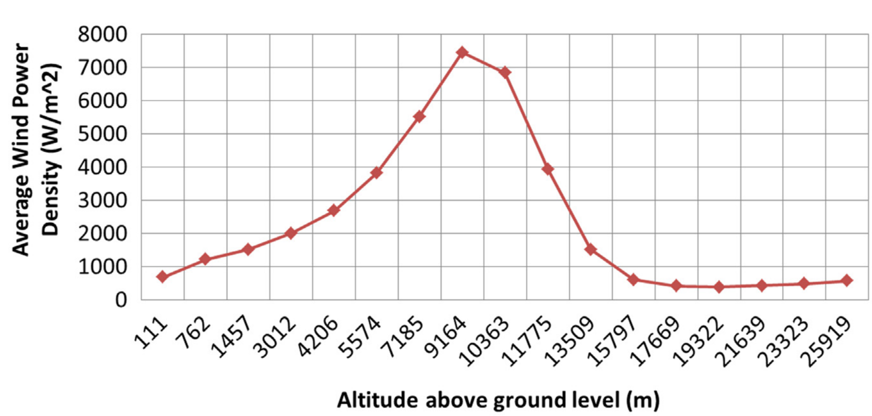

Fig. 3. Wind power density averaged over a 20-year time span across various pressure level heights.

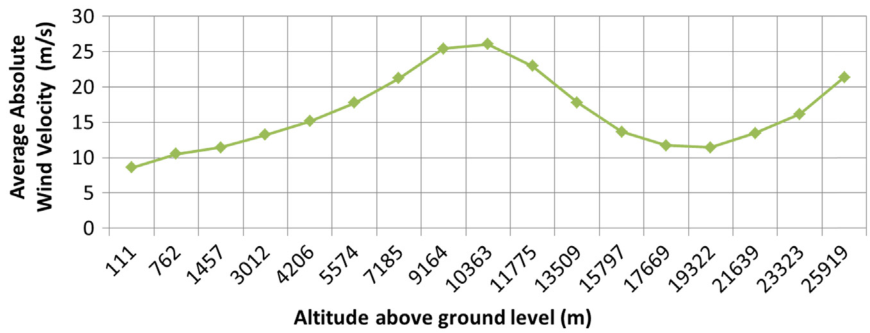

Fig. 4. Absolute wind velocities averaged over a 20-year time span across various pressure levels.

3.10. Initial budget for the project demonstrator

An initial budget was prepared in Table 3 outlining the equipment and resources needed to set-up and build a 2 MW PKG. The findings present a preliminary cost estimate of £1,751,401.73 per unit.

This approximation proves to be economically viable when compared to conventional wind technology of similar power rating, valued at £3,000,000 by the Energy Saving Trust [55]. The variance in cost is primarily due the lower embodied energy of a PKG, replacing the rotor with a wing and no tower structure required, reducing the balance of station costs significantly. A HAWP device is easily transportable, within a single transfer, in comparison to that of CWT, which requires each section to be delivered to site separately. Maintenance can also be carried out at ground level for the PKG, leaving it much more accessible for operation ground teams. The Levelized Cost of Energy (LCOE) was calculated for the 2 MW project demonstrator, using the outputs from Table 3 [56]. A fixed charge rate (FCR) of 11.85% was established for wind farm financing [52] and the annual energy production (AEP) was calculated utilizing a capacity factor of 60%. The LCOE for the project demonstrator was 0.106£/kWh, which is moderately higher when assessed against the average cost of electricity from large-scale onshore wind at 0.03–0.04£/kWh [55]. This finding reflects the prematurity of this technology, and is predominantly accountable due to the excessive annual operation expenses, calculated to be 639.93£/kW/year, mainly due to the frequent kite replacement costs as a result of material degradation in unknown and unchartered conditions.

4. Discussion

This in-depth state-of-the-art review of HAWP has revealed that the field is very active with a number of patents and prototypes at various stages of development. The technical and economic feasibility of HAWP in Northern Ireland was also evaluated using MATLAB and ArcGIS. The preliminary visualisation analysis displays the wind power densities ranging from 1850 to 2100 W/m^2 averaged over a 20-year span at a set height of 3000 m for Northern Ireland. This power density encourages the technical viability of HAWP in this region with an average of 1998 W/m^2 over the entire 20-year span at 3000 m, in comparison to a similar study carried out in southeast Europe, which attained a much lower average of 371 W/m^2 at a set altitude of 2500 m [65].

It is evident that the west of Northern Ireland are subjected to the highest HAWP densities of 2050 W/m^2 and above, primarily in County Fermanagh and the west of County Tyrone, proving beneficial for future plans in selecting optimal locations to utilise HAWP as a renewable power source. On the subject of wind power density, an average was obtained for each pressure level height across the 20-year assessed period (as seen in Fig. 3) with a peak power density of 7443.4 W/m^2 at an altitude of 9164 m. This replicates the findings in [5], a global assessment of HAWP thus validating that the highest wind power densities are found at altitudes between 8000 and 10,000 m agl and above 2000 m wind power densities increase monotonically with height, with relatively constant wind power densities between 500 m and 2000 m [5].

As wind power density is proportional to the third power of wind speed, fluctuations of wind speed have a knock on effect on wind power output. Fig. 4 displays the averaged absolute wind velocities over the time sample at various pressure level heights. These results emulate those in Fig. 3 with a gradual increase in wind speed occurring between 3000 m and 9000 m peaking at an absolute wind speed of 26.06 m/s at around 10,000 m. These findings support the initial considered locality for HAWP technology to be above the earth's neutral ABL at 1300 m agl and it emerges that the maximum optimal altitude height worth exploring for HAWP technologies in Northern Ireland is 10,000 m, which seems very challenging.

An issue that needs to be considered when locating a site for HAWP like WP is proximity to an available grid connection. The grid owner in Northern Ireland stated in the latest Renewables Integration Status Report [66], that it is confronted with an unprecedented demand for the connection of renewable generation. The Northern Ireland 'electricity heat map' [67] displays that network limitations for small scale generation are either at or reaching saturation point in the west of Northern Ireland, and as a result connection costs are likely to be very high, with only limited potential remaining for additional generation export. It can also be identified that numerous primary substations are reaching their capacity limit.

Although, this analysis has shown the potential of HAWP in Northern Ireland, there are limitations to this study and future research steps have been identified. Firstly in relation to the geographical limitations of the study, only large towns and towns were selected from the settlement data, excluding the villages and small villages of Northern Ireland from the analysis. Considering the transport data, only motorways and railways were identified, excluding other transport links such as dual-carriage ways and A-Class roads. If these omissions were included in the analysis, a very different outcome would emerge, reconfiguring the viable sites to a much lower area coverage. This analysis could be re-undertaken at a higher resolution to include more detailed geographical limitations (e.g. grid connections and population densities). Secondly, to complete the economic analysis an initial budget cost for a PKG was prepared as the project demonstrator, principally because it was the only HAWP device with published design parameters. This type of HAWP device does not operate to the selected altitude of 3000 m chosen for the wind power density analysis, but instead within an altitude range of 600 m to 1000 m.

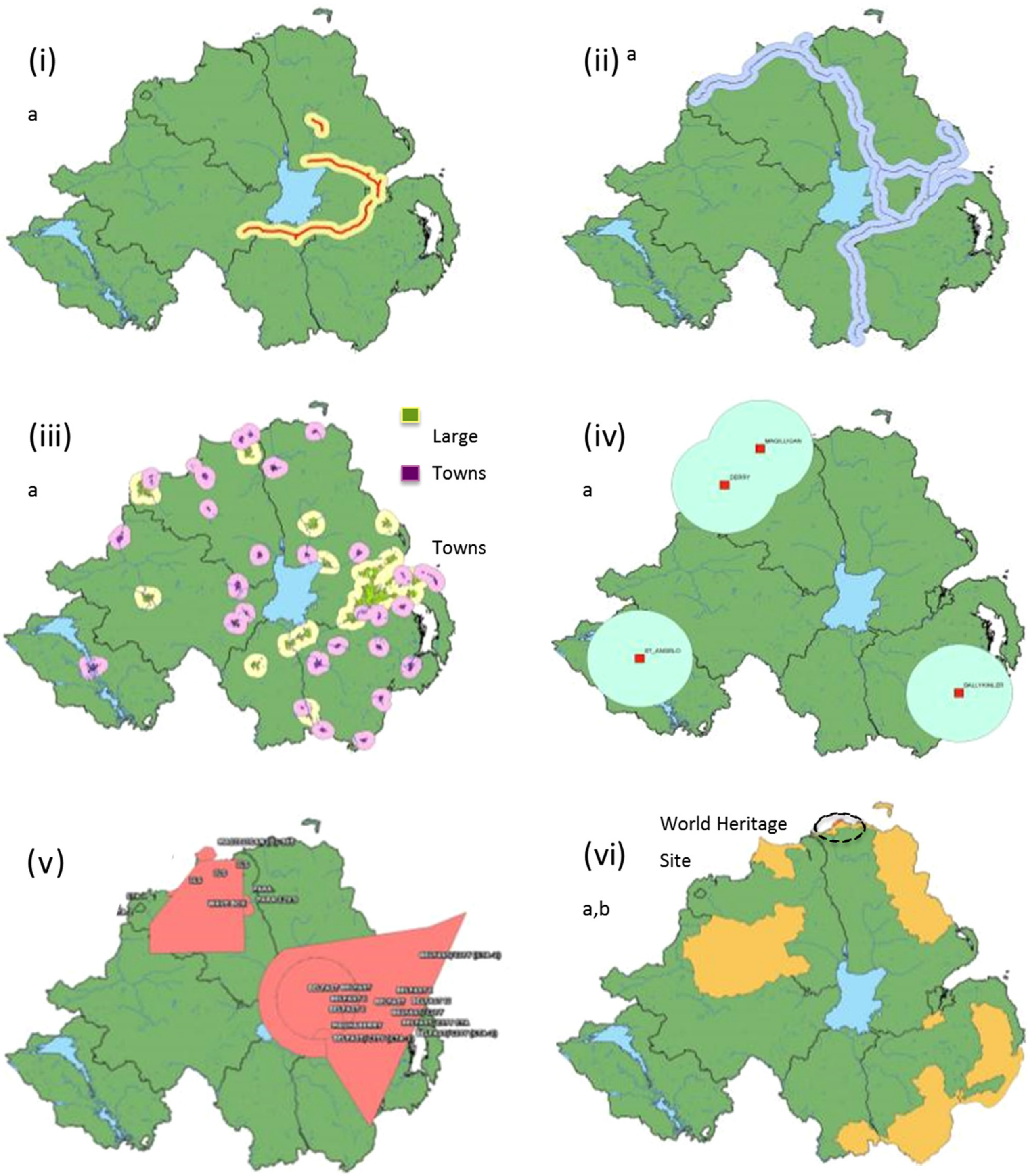

Fig. 5. All geographical limitation layers over Northern Ireland: (i) motorways, (ii) railways, (iii) settlements, (iv) airports and military training areas, (v) controlled airspace, (vi) world heritage site & areas of outstanding natural beauty, (vii) areas of special scientific interest, (viii) special areas of conservation, (ix) all restricting layers are merged together in red, leaving visible the potential locations for HAWP devices. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A costing of a tethered rotorcraft, which operates at the selected analysis altitude, would have perhaps provided a better techno-economic comparison. Thirdly, in the initial budget, the assumptions and calculations carried out as a means of costing the project demonstrator carry a large value of uncertainty due to the limitations in accessing HAWP economic and technical data. It is recommended that in the future the economic viability of HAWP in Northern Ireland be carried-out again once better costings (and technical data) become available. It is also recommended that the analysis area be expanded to include the Republic of Ireland.

5. Conclusion

This techno-economic study indicates that there is potential for HAWP in Northern Ireland, predominantly in the south and south

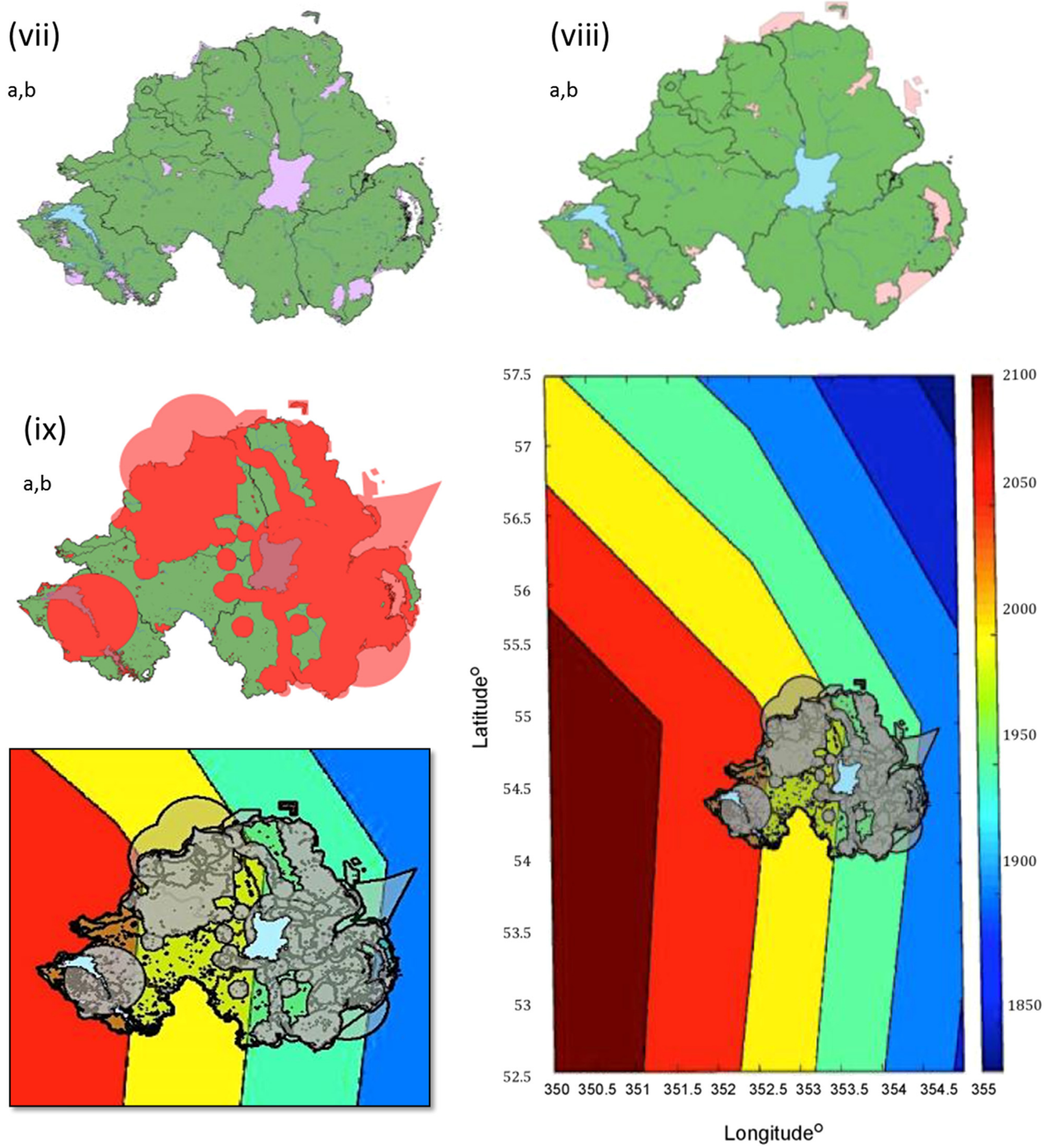

Fig. 6. Final visualisation map displaying the average high altitude wind power density (W/m^2) for Northern Ireland at 3000 m agl identifying geographical limitations.

west. The specific technical findings of the study are summarised as follows:

- There is huge potential for HAWP in Northern Ireland with a wind power density ranging from 1850 W/m^2 to 2100 W/m^2, with an average of 1998 W/m^2, at a set height of 3000 m, averaged over a 20-year span.
- The highest wind power densities occur off the west coast of Northern Ireland attaining wind power densities in excess of 2050 W/m^2.
- The onshore western areas of Northern Ireland are subjected to the highest wind power densities of 2050 W/m^2 and above with the most suitable site for a demonstrator high altitude wind project located in the west of County Tyrone.
- The total viable area across Northern Ireland for siting a HAWP device was determined to be 5109.6 km^2.
- At 3000 m, the maximum height chosen for the study, the average absolute wind velocity was 13.25 m/s.
- These technical findings support the initial considered locality for this innovative technology to be above the earth's neutral ABL, at 1300 m above ground level.
- The maximum optimal altitude height worth exploring for HAWP technologies in Northern Ireland is 10,000 m.
- The average power density variations were found to be below

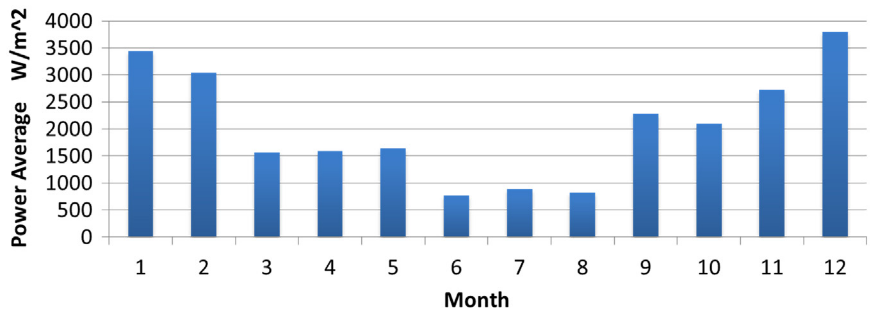

Fig. 7. Wind power density averaged by month from 2010 to 2013 to a height of 3000 m over Northern Ireland.

Table 3
Initial budget of demonstrator.

Initial Capital Costs (ICC)	Lower boundary	Higher boundary	Mean (£)
Kite	167,705	244,849	206,277
Kite Control Unit	33,333	50,000	41,667
Mechanical Systems			
Tether (x2)	4533	6800	5667
Winch Drum (Inc. Line Handling & Bearings) (x2)	4469	4702	4585
Electrical Systems		**Total (€)**	**Total (£)**
Generator		14,567	10,634
Power Electronics		10,734	7836
Yaw Drive & Bearing		530	387
Hydraulic & Cooling Systems		1303	951
Ground Station & Cover Frame		6529	4766
Balance of Station (BOS)		**Total (€)**	**Total (£)**
Foundation	10% of CWT	16,000	11,680
Road Construction	30% of CWT	6600	4818
Electrical Installation	50% of CWT	18,000	13,140
Grid Connection		218,000	159,140
TOTAL ICC		£	471,547
Annual Operating Expenses (AOE)			**Total (£)**
Based on a capacity factor of 60%, operational for 5256 h/year			
Replacement Costs	**Life span**	**No. of replacements**	
Kite	1000 h	6	1,237,664
Kite Control Unit	5 years	0	8333
Tether	10,000 h	1	2833
Operations & Maintenance			10,000
Land Lease	30% of CWT		21,024
TOTAL COSTS OF PROJECT DEMONSTRATOR (Year 1)	£		1,751,402

80%, exemplifying HAWP is significantly influenced by seasonal changes.

- The geographical limitations that are most restricting in terms of available area for HAWP sites are controlled airspace and areas of outstanding natural beauty.

The specific economic findings of the study are summarised as follows:

- An initial budget for a 2 MW HAWP PKG indicated a total cost £1,751,402 per unit.
- The LCOE for the project demonstrator was determined to be 0.106£/kWh.

In conclusion, this study has shown that HAWP is an active area of technology research and development. Although still in its infancy there appears to be potential for HAWP as demonstrated by the key findings of the case study on Northern Ireland. However, this potential can only be achieved once this unproven novel technology reaches a more advanced stage of development.

Acknowledgements

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